

## Design and Performance Analysis of a Hybrid Inverter for Solar and Wind Energy System

R. Gopalakrishnan<sup>1</sup>, V. Heama Chandran<sup>2</sup>, T. Shomesh<sup>3</sup>, M. Kamalesh<sup>4</sup>

<sup>1</sup>Assistant professor, Department of EEE, Kongunadu College of Engg. & Tech., Tiruchirappalli, Tamil Nadu, India.

<sup>2,3</sup>UG Scholar, Department of EEE, Kongunadu College of Engg. & Tech., Tiruchirappalli, Tamil Nadu, India.

<sup>4</sup>UG Scholar, Department of CSE, Kongunadu College of Engg. & Tech., Tiruchirappalli, Tamil Nadu, India.

**Emails:** gopalakrishnanr@kongunadu.ac.in<sup>1</sup>, heamachandranv20@gmail.com<sup>2</sup>, shomesh.0007@gmail.com<sup>3</sup>, mkamaleshkamalesh88@gmail.com<sup>4</sup>

### Abstract

*This paper focuses on the design and implementation of a hybrid inverter for solar and wind energy systems, aimed at enhancing renewable energy utilization. The inverter integrates power from both sources, optimizing energy conversion and ensuring efficient delivery to the load or grid. Advanced power electronics and control strategies are employed to manage the variable inputs from solar panels and wind turbines. The system is designed to provide seamless operation, including energy storage management and grid synchronization. Emphasis is placed on maximizing efficiency, reliability, and cost-effectiveness. Real-time monitoring and adaptive algorithms enhance performance under varying environmental conditions. The project also includes hardware prototyping and testing to validate the design's functionality and robustness. This hybrid inverter serves as a sustainable solution for decentralized renewable energy systems, contributing to global energy needs.*

**Keywords:** Hybrid Inverter, Renewable Energy, Solar and Wind Integration, Energy Conversion, Performance Optimization, Environmental Adaptation, Grid Synchronization, Energy Utilization.

### 1. Introduction

The growing need for clean and renewable energy has driven the development of hybrid energy systems that combine multiple sources, such as solar and wind power, to create a more stable and efficient power supply. Solar and wind energy are among the most abundant and eco-friendly resources available, but their intermittent nature poses challenges in ensuring a consistent and reliable energy output. Solar power generation depends on sunlight, while wind energy fluctuates with changing wind speeds. A hybrid system that integrates both sources can balance these variations, offering a more dependable and efficient solution. To maximize the benefits of a hybrid renewable energy system, an efficient power conversion and management strategy is essential. This is where a hybrid inverter plays a crucial role. Unlike traditional inverters that handle only a single energy source, a hybrid inverter is designed to manage the integration of both solar and wind power, ensuring smooth energy flow and optimal power utilization. By intelligently controlling power input

and output, it enhances efficiency, stabilizes voltage, and reduces energy losses, making hybrid energy systems more practical for real-world applications. This study focuses on the design and performance analysis of a hybrid inverter that connects solar photovoltaic (PV) panels and wind turbines. The proposed inverter incorporates advanced power electronics and control algorithms, such as Maximum Power Point Tracking (MPPT), to extract the highest possible energy from both sources. It is designed to handle dynamic environmental conditions, ensuring a steady and uninterrupted power supply. Through simulations and real-time testing, we assess its efficiency, voltage stability, and overall performance under different operational scenarios. The performance evaluation involves analyzing key parameters such as energy conversion efficiency, power quality, response to load variations, and adaptability to fluctuating weather conditions. By comparing results with conventional inverter systems, this study highlights the advantages of using

a hybrid inverter in renewable energy applications. The insights gained from this research can contribute to the improvement of hybrid energy technologies, supporting the global transition toward cleaner and more sustainable energy solutions. Ultimately, this research aims to bridge the gap between theoretical advancements and practical implementation of hybrid inverters in renewable energy systems. By developing a robust and efficient inverter, we can improve the reliability of hybrid solar-wind power generation, making it a viable option for residential, commercial, and industrial applications. The findings from this study serve as a stepping stone toward smarter and more adaptable renewable energy solutions, paving the way for a greener and more sustainable future [1].

## 2. Literature Review

The integration of solar and wind energy systems has been widely studied as a solution to the intermittency issues of individual renewable sources. Solar panels generate power only during daylight hours, while wind turbines depend on wind speed variations, making a hybrid system a more stable and efficient alternative. Researchers have explored different methods to optimize power conversion in such systems, with a particular focus on hybrid inverters. Unlike conventional inverters designed for single energy sources, hybrid inverters efficiently manage multiple inputs, ensuring smooth power flow and reducing energy wastage. Several studies highlight the importance of these inverters in improving overall system reliability, grid integration, and energy management. A significant area of research in hybrid inverters involves Maximum Power Point Tracking (MPPT) techniques, which help maximize energy extraction from both solar and wind sources. Various MPPT algorithms, such as Perturb and Observe (P&O), Incremental Conductance (INC), and Adaptive Neuro-Fuzzy Inference Systems (ANFIS), have been proposed to improve efficiency. While these techniques have been effective in optimizing power output, challenges remain in adapting to rapid environmental fluctuations. Recent advancements suggest that combining multiple MPPT strategies or integrating artificial intelligence-based control mechanisms can enhance inverter responsiveness,

leading to better performance and energy utilization. Another crucial aspect studied in hybrid inverter design is the role of power electronics and energy storage integration. Modern inverters incorporate high-efficiency semiconductor devices like IGBTs and MOSFETs to improve switching performance and minimize power losses. Additionally, research has explored the integration of battery storage systems to stabilize power output and ensure uninterrupted energy supply during low-generation periods. However, challenges such as cost, system complexity, and long-term durability remain key concerns. This study builds on existing research by designing and analyzing a hybrid inverter that not only maximizes energy efficiency but also enhances adaptability, offering a more practical solution for hybrid solar-wind energy applications [2-7].

## 3. Flat Panel Photovoltaic Systems

Flat panel photovoltaic (PV) systems generate direct current (DC) electricity in proportion to the amount of sunlight they receive. Each module is designed to provide electricity at a specific voltage, while the amount of current produced depends on the intensity of light absorbed. By connecting multiple panels in series or parallel configurations, different voltage and current levels can be achieved to meet specific energy requirements. These PV panels consist of modules, which are further made up of individual PV cells. Each cell is a thin semiconductor wafer, typically made of silicon or selenium, and is treated with boron (p-type) and phosphorus (n-type) to enhance conductivity and create an electric field that enables electricity generation. A complete PV system is more than just the panels; it also includes various supporting components known as the Balance of System (BOS). These components help optimize energy production and may include mounting structures to position the panels for maximum sunlight exposure, inverters to convert DC electricity into usable alternating current (AC), batteries for energy storage, and backup generators for additional reliability. Other BOS components may include maximum power point trackers (MPPT), solar irradiance sensors, GPS solar trackers, energy management software, and even anemometers for wind measurements. When combined, these elements

form a fully functional PV system capable of powering anything from a single appliance to an entire home or community. Flat panel PV systems are the most common renewable energy installations, particularly in the United States. On a clear day, the sunlight reaching the Earth's surface delivers approximately 1,000 watts of power per square meter. A single flat panel typically consists of at least 600 PV cells and can generate between 5 to 300 volts depending on sun exposure. However, individual panels are rarely sufficient for large-scale applications, so multiple panels are interconnected in various configurations to form larger arrays. These arrays, commonly seen on rooftops or large open fields, can deliver voltage in multiples of 12V and current in multiples of 3A, making them highly adaptable to different energy demands. For PV systems that supply electricity back to the grid, an inverter is essential to convert DC power into AC power while synchronizing with the utility grid. Modern grid-tied inverters are highly efficient, allowing the PV array to operate at its maximum power point (MPP) under all conditions. These inverters ensure that the AC output is in phase with the utility grid voltage and can achieve power conversion efficiencies close to 100%. Some advanced inverters also integrate energy storage capabilities, helping balance the power supply between the DC-generated electricity from the PV system and the AC requirements of the grid. This combination of solar power generation and efficient energy management makes PV systems a vital component in the transition toward sustainable energy solutions [8-12].

#### 4. Wind Turbine Systems

Wind power systems harness the natural movement of air to generate electricity. When the wind blows, it applies force to the turbine's rotor blades, causing them to spin. This rotational motion is then transferred to a generator, which converts the kinetic energy into direct current (DC) electricity. The two most important factors influencing power generation are wind speed and wind quality. Obstructions like buildings and turbulent atmospheric conditions can disrupt airflow, reducing efficiency. For this reason, wind turbines are typically installed in elevated, open

areas where they can capture the most consistent and powerful wind currents. Unlike solar power systems, which rely on chemical and thermal reactions to generate electricity, wind turbines operate through pure mechanical energy conversion. Their design is relatively straightforward, with the most visible and essential components being the rotor blades. These blades are carefully shaped to maximize energy capture, efficiently transferring wind energy into rotational motion. As the blades spin, they turn a rotor, which then drives a central shaft connected to the generator. The generator is the heart of the wind turbine, functioning similarly to an electric motor. Inside, the rotating shaft spins a rotor within a stator (the stationary component of the system). This motion creates a changing magnetic field, inducing an electrical current that can be harnessed as usable power. Essentially, the generator transforms the mechanical energy from the wind into an electromotive force (EMF), which is then converted into electricity. By utilizing this simple yet effective process, wind turbines provide a clean and sustainable source of energy, making them a vital part of the global transition toward renewable power solutions. To enhance efficiency and adaptability, modern wind turbines incorporate advanced control systems that optimize performance based on wind conditions. Features such as pitch control adjust the angle of the blades to capture the maximum possible energy, while yaw control ensures the turbine is always facing the wind. Additionally, many wind power systems integrate battery storage solutions to store excess electricity for use during periods of low wind activity. As technology continues to evolve, improvements in materials, aerodynamics, and energy storage are making wind energy more reliable and cost-effective, reinforcing its role as a key player in the future of renewable energy.

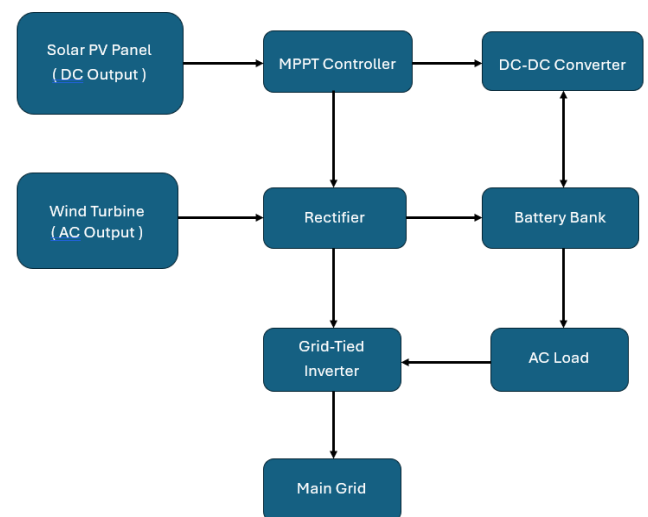
#### 5. Hybrid PV/Wind Micro-Grids

The increasing global demand for clean and sustainable energy has accelerated the adoption of hybrid photovoltaic (PV) and wind micro-grids as a viable solution for reliable power generation. A hybrid PV/wind system integrates solar and wind energy to enhance efficiency, reduce intermittency, and ensure a continuous power supply. Since solar

and wind resources exhibit complementary generation patterns—solar energy peaks during the day and in summer, while wind energy is often stronger at night and during winter—this combination significantly improves energy availability and system reliability. By leveraging both renewable sources, hybrid micro-grids optimize energy production and minimize dependency on conventional fossil-fuel-based electricity, making them an essential component of modern energy infrastructure. Hybrid PV/wind micro-grids can operate in grid-tied or off-grid configurations, depending on their application. In a grid-connected system, excess power generated can be fed back into the main power grid, reducing electricity costs for consumers and contributing to energy sustainability. This approach eliminates the need for extensive battery storage, which is often a cost-intensive component in renewable energy systems. However, in off-grid or remote locations, energy storage is crucial to ensure a stable power supply during periods of low solar or wind activity. To address this challenge, hybrid systems integrate battery banks, energy management controllers, and advanced power electronics to optimize energy utilization and storage, ensuring uninterrupted power delivery. One of the critical challenges in hybrid PV/wind micro-grids is maintaining stable voltage and frequency levels, especially in grid-tied applications. To ensure smooth energy integration, power electronic converters play a pivotal role in regulating voltage, managing power flow, and optimizing efficiency. The incorporation of Cuk converters and SingleEnded Primary Inductor Converters (SEPIC) in hybrid systems enhances energy conversion by stabilizing power fluctuations and improving overall performance. Additionally, Maximum Power Point Tracking (MPPT) algorithms are utilized to maximize energy extraction from both solar panels and wind turbines under varying environmental conditions, further increasing system efficiency. Although hybrid PV/wind systems require a higher initial investment compared to standalone solar or wind setups, they offer substantial long-term benefits. Their ability to generate power from multiple sources improves overall system efficiency, leading to higher energy yields, lower operational

costs, and a greater return on investment (ROI). Additionally, these systems contribute to significant carbon footprint reduction, supporting global initiatives toward decarbonization and energy sustainability. As advancements in battery storage, artificial intelligence-based energy management, and smart grid technologies continue to emerge, hybrid micro-grids are becoming increasingly efficient, adaptive, and cost-effective. The adoption of hybrid PV/wind micro-grids represents a transformative shift toward a more resilient, decentralized, and sustainable energy landscape. These systems provide energy security, operational flexibility, and enhanced grid stability, making them a highly effective solution for diverse applications, including residential, commercial, and industrial power generation. With continuous technological advancements and policy support, hybrid PV/wind micro-grids have the potential to redefine the future of renewable energy integration, paving the way for a cleaner and more sustainable world.

## 6. Proposed System



**Figure 1 Block Diagram of the Proposed System**

Figure 1 shows the basic block diagram of the proposed scheme. The proposed hybrid PV/Wind microgrid system efficiently combines solar and wind energy to ensure a stable and reliable power supply. Solar panels generate DC power, managed by an MPPT controller, while the wind turbine produces



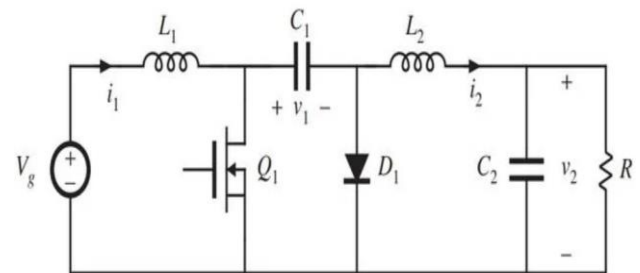
AC power, which is converted to DC using a rectifier. A Cuk and SEPIC converter stabilizes the voltage for smooth energy transfer. Excess energy is stored in a battery bank to ensure continuous power availability. A grid-tied inverter converts DC to AC, allowing seamless integration with AC loads or feeding surplus energy into the utility grid. This system enhances energy efficiency, reliability, and sustainability, making it an ideal solution for decentralized renewable power generation.

### 7. Power Supply

The power supply system in a hybrid solar and wind energy setup is designed to efficiently manage energy generation, conversion, and distribution. The system integrates solar photovoltaic (PV) panels and wind turbines as primary energy sources, ensuring continuous power availability. Since both sources generate DC power, it is essential to condition and regulate the output voltage before supplying it to the load. This is achieved using Cuk and SEPIC converters, which help in voltage regulation and power flow control. These converters optimize energy transfer from both sources, ensuring stable power delivery to the battery storage and inverter system. The battery bank plays a crucial role by storing excess energy, which can be utilized during low-generation periods, such as nighttime for solar or calm weather for wind energy. The hybrid inverter serves as the heart of the system, converting DC power from batteries into AC power required by household appliances, industrial loads, or even the utility grid. A charge controller is included to regulate the charging and discharging cycles of the battery, preventing overcharging and deep discharge, thus extending battery life. The integration of a smart energy management system allows for real-time monitoring, optimizing power flow, and ensuring seamless transition between energy sources. By combining solar and wind energy, this hybrid system maximizes energy efficiency, minimizes reliance on conventional grid electricity, and promotes sustainability. The following block diagram illustrates the entire power supply architecture, showing how different components work together to ensure a reliable and efficient power system.

### 8. Multi-Input Converters

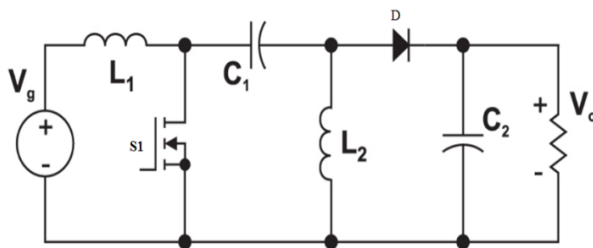
In hybrid renewable energy systems, multi-input converters (MICs) play a crucial role in efficiently integrating multiple power sources, such as solar PV and wind energy, into a unified power management system. Unlike traditional converters that handle a single energy source, MICs are designed to process and regulate power from multiple inputs, ensuring optimal energy utilization and seamless power flow. One of the key advantages of MICs is their ability to manage varying power levels from different sources, compensating for fluctuations in solar irradiance and wind speed. By incorporating advanced control strategies like Maximum Power Point Tracking (MPPT) for PV systems and adaptive control algorithms for wind turbines, MICs maximize energy extraction while maintaining system stability. Additionally, they enable power sharing between sources, reducing dependency on energy storage and enhancing system reliability.



**Figure 2 Cuk Converter Operating Under Solar Source**

Figure 2 illustrates the given circuit represents a Cuk Converter, a type of DC-DC converter designed to provide a regulated output voltage that can be either higher or lower than the input voltage while maintaining polarity inversion. The converter consists of key components such as inductors ( $L_1$  and  $L_2$ ) for energy storage, capacitors ( $C_1$  and  $C_2$ ) for voltage smoothing, a switching transistor ( $Q_1$ ) for energy transfer control, and a diode ( $D_1$ ) for directing current flow. The operation relies on energy transfer between inductors and capacitors, ensuring minimal ripple and improved efficiency. Due to its continuous current characteristics, the Cuk converter is widely used in applications requiring efficient voltage regulation with reduced electromagnetic interference.

Figure 3 illustrates the given circuit represents a SEPIC (Single-Ended Primary Inductor Converter), which is commonly used in wind energy systems for efficient DC-DC power conversion. The SEPIC converter allows the output voltage ( $V_o$ ) to be either higher or lower than the input voltage ( $V_g$ ), making it highly suitable for fluctuating wind power sources. The circuit consists of inductors ( $L_1$  and  $L_2$ ) that ensure continuous current flow, capacitors ( $C_1$  and  $C_2$ ) for energy storage and voltage stabilization, a switch ( $S_1$ ) (typically a MOSFET) for controlled energy transfer, and a diode ( $D$ ) to direct current flow. This topology ensures stable voltage regulation, making it ideal for integrating wind energy into hybrid renewable systems.



**Figure 3 SEPIC Converter Operating Under Wind Source**

## 9. Inverter Reliability

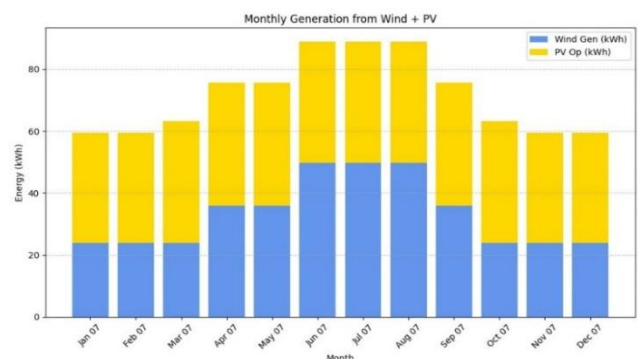
A dependable power backup option made to keep homes and businesses operating smoothly during blackouts is a 2 kVA, 24V pure sine wave inverter. It guarantees effective power conversion while preserving a steady voltage output thanks to cutting-edge digital technology. Because of its pure sine wave output, it may be used with delicate electronics, protecting them from harm and guaranteeing seamless performance for gadgets like computers, televisions, and medical equipment. With real-time insights into battery levels and power condition, its smart LCD display and soft-touch controls simplify operation and monitoring. Safety is more important than performance. To ensure longevity and dependability, this inverter is outfitted with several layers of protection, such as overload, short circuit, battery overcharge, and temperature precautions. It is perfect for appliances with motor-driven parts, such as air conditioners and refrigerators, because it can

manage strong surge loads. Additionally, by streamlining the charging process and offering a range of battery capacities from 100 Ah to 200 Ah for longer backup times, intelligent battery management prolongs battery life.

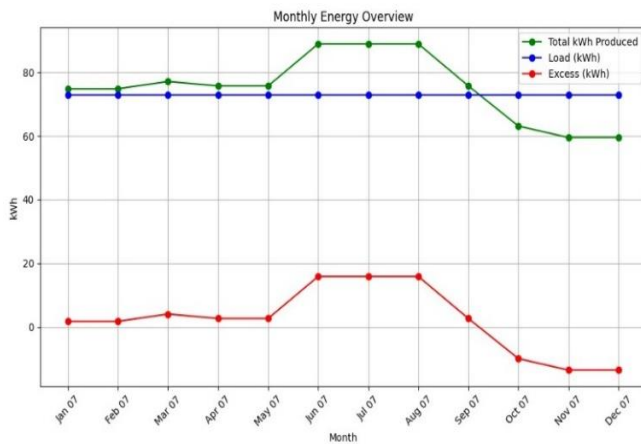
**Table 1 Monthly Hybrid Energy Analysis**

Month	Wind Speed (m/s @ 18m)	Wind Generator O/P (kWh)	PV O/P (kWh)	Total (kWh)	Total Internal Load (kWh)	Excess (kWh)
Jan 07	3.1	39.2	35.6	74.8	73.0	1.8
Feb 07	3.1	39.2	37.8	77.0	73.0	4.0
Mar 07	3.1	39.2	39.3	78.49	73.0	5.49
Apr 07	3.1	39.2	36.9	76.12	73.0	3.12
May 07	3.1	39.2	37.4	76.63	73.0	3.63
Jun 07	5.4	177.6	30.7	208.34	73.0	135.34
Jul 07	5.4	177.6	22.2	199.82	73.0	126.82
Aug 07	5.4	177.6	21.1	198.68	73.0	125.68
Sep 07	4.9	147.2	25.6	172.85	73.0	99.85
Oct 07	3.6	61.6	37.1	98.7	73.0	25.7
Nov 07	3.1	39.2	37.3	76.47	73.0	3.47
Dec 07	3.1	39.2	34.7	73.87	73.0	0.87
TOTAL (avg.)	3.9	1016	395.8	1411.8	876	

Table 1 illustrates the detailed analysis of monthly energy generation and consumption in a hybrid wind and solar energy system. It includes data on wind speed at 18m height, energy output from the wind generator, photovoltaic (PV) output, total energy generated, internal load consumption, and excess energy available. The average wind speed for the year is 3.9 m/s, with higher wind energy outputs observed during June, July, and August, contributing significantly to the total energy generation. The system consistently meets the internal load requirement of 73 kWh per month, with surplus energy during most months, particularly in the windy season, demonstrating the system's efficiency and reliability.



**Figure 4 Monthly Energy Generation from Wind and Solar PV System**



**Figure 5 Energy Overview**

## 10. Battery Storage Integration and Energy Management Strategies

In a solar and wind hybrid system, battery storage is essential for a constant and dependable supply of power. Both solar and wind are intermittent in nature—based on sunlight and wind velocity—and thus batteries function as a standby, accumulating extra power when it is produced abundantly and delivering it when there is a need. Selecting the correct battery, either lithium-ion, lead-acid, or any other advanced storage, is a function of efficiency, cost, lifespan, and maintenance. For maintaining batteries in good health, a Battery Management System (BMS) is required. It assists in managing charging and discharging, overloading prevention, and long-term reliability, which makes the entire system more reliable. Efficient management of energy flow is equally critical as its storage. An intelligent energy management system determines whether to store energy, utilize it, or retrieve from the grid when necessary. It does so with the aid of smart controllers that regulate energy from solar, wind, and batteries to achieve energy demand in a balanced form. Maximum Power Point Tracking (MPPT) is another very important method by which maximum renewable energy is utilized and efficiency improved. Furthermore, predicting electricity consumption and optimizing usage patterns can further maximize energy supply, minimize wastage, and decrease costs. With technological advances, new hybrid systems are becoming more intelligent and efficient. Artificial Intelligence (AI) and the Internet of Things (IoT) are

now being incorporated to forecast power output based on weather patterns and real-time energy consumption patterns. Smart grids, powered by IoT, allow remote monitoring and automated control of energy flow, making the system more user-friendly and efficient. By leveraging these innovations, hybrid renewable energy systems are becoming a more practical and sustainable solution for homes, businesses, and industries, ensuring clean energy availability around the clock. Battery storage minimizes the use of fossil fuels by optimizing the use of renewable energy. Sophisticated energy management provides voltage stabilization and enhanced power quality, making systems more resilient. Decentralized storage maintains grid stability and microgrids in isolated locations. Emerging technologies such as solid-state batteries will increase efficiency and sustainability even further, shown in Figure 4 & Figure 5.

## Conclusion

The data clearly demonstrates the effectiveness of a hybrid renewable energy system in consistently meeting internal energy demands while also generating excess power in certain months. Over the year, the system produced a total of 1,411.8 kWh, significantly surpassing the internal load requirement of 876 kWh. This highlights the system's efficiency and reliability in supplying continuous energy, even during months with lower wind speeds. The highest surplus was observed during peak wind months, such as June, July, and August, showing the crucial role of wind energy in boosting overall output. These findings reinforce the viability of hybrid systems in ensuring energy stability while reducing reliance on conventional power sources. By optimizing both wind and solar resources, the system not only meets energy demands but also generates excess power that could be stored or redirected for other applications. This research underscores the potential of hybrid renewable energy solutions in promoting sustainable energy practices and minimizing environmental impact, paving the way for a greener and more energy-efficient future.

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